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10 Autonomous Systems for Emergency and Stability Control of FACTS

The requirement specification in chapter 9 has clearly shown, that the uncoordinated use of FACTS-devices involves some negative effects and interactions with other devices, which leads to an endangerment of the steady-state and dynamical system security. This chapter shows one approach to overcome these difficulties and provides a solution for a coordinated control system fulfilling the specified requirements.

An autonomous control system for electrical power systems with embedded FACTS-devices is developed that provides the necessary preventive coordination. With methods of computational intelligence the system automatically generates specific coordinating measures from specified abstract coordinating rules for every operating condition of the power system without human intervention or control. This guarantees an optimal utilization of the technical advantages of FACTS-devices as well as the steady-state and dynamical system security. Interactions between the autonomous system and other existing controllers in electrical power systems are taken into consideration so that the autonomous system can completely be integrated into an existing conventional network control system.

10.1 Autonomous System Structure

The response time of FACTS-devices is in the range of some ten milliseconds. In case of critical events within the power system, e.g. faults or overloadings, FACTS-devices react immediately to these events due to their short response time. If the FACTS-devices are not adapted to the situation in and after such a critical event, this can lead to an endangerment of the steady-state and dynamical system security. The Non-Intrusive System Control (NISC) approach in chapter 9 defined the necessary interactions for regular and emergency control of FACTS-devices.

As a consequence, the application of FACTS-devices requires both a fast coordination of their controllers among one another and with power plants, loads, and conventional controlling devices within the power system. This coordination must guarantee the steady-state and dynamical system security in the case of critical events and has to be automatic, quick, intelligent, and preventive.

The NISC approach has separated the planning phase for coordinating actions from their local execution. One step further goes the autonomous system approach, where clearly separated autonomously acting components provide specific

tasks. These tasks are in this case system analysis, coordination and execution of the specified control task. Autonomous systems generally represent an abstract information-technological framework, which is specified in detail in [1]. Generally its architecture can be subdivided into several intelligent autonomous components communicating with each other.

The autonomous components themselves consist of different authorities called 'management', 'coordination', and 'execution'. Depending on the control level on which an intelligent autonomous component is placed, one of the three authorities dominates compared to the other two authorities. In order to specify the components on each control level every necessary local controller of the process must be determined concerning its structure. An autonomous component can be a control station, a process computer or a simple controller.

According to the hierarchical model of a control system for complex technical processes, e.g. electric power systems, the different control levels are called:

- network control level,
- substation control level,
- bay control level.

Bay Control Level. The physical coupling of the autonomous components on the bay control level is realized by sensors and actuators. The main task at the bay control level is 'execution', i.e. in this context mainly the application of control and adaptation algorithms.

Substation Control Level. Autonomous components on the substation control level mainly act as coordinators. They determine and plan the functionality of other components and delegate distinct special tasks.

Network Control Level. On the network control level autonomous components are working with information being generated from a model of the whole process, which can be implemented on this control level. The most important task of these components is the decomposition of global aims being generated here or prescribed by a human operator through the human-machine-interface.

The main capability of an autonomous control system is to act automatically without manual interactions. The autonomous system shall provide the following features:

- perform self-learning, self-organization, and can plan and optimize control actions,
- decentralized artificial intelligence enables quick autonomous actions.
- automatically adaptation to changes of the technical process in structure and parameters,
- operation of the process without human intervention.

To achieve this, some kind of knowledge about the required coordinating actions and adaptations must be embedded into the system on the specific levels. As a solution coordinating generic rules can be defined which are valid in any power sys-

tem. These rules have to be adapted by a system analyses to the specific operational conditions.

10.2 Autonomous Security and Emergency Control

10.2.1 Model and Control Structure

In the following the autonomous system control will be demonstrated by the means of UPFC. The reason is that the UPFC provides fast power flow, voltage and damping control and therefore requires especially the coordinating control scheme. Other simpler FACTS-device controls can be derived from this general structure.

As shown in Fig. 10.1 the dynamic behavior of a UPFC can be modeled by a current source injecting the shunt current $\bar{I}_q$ and a voltage source inserting the longitudinal voltage $\bar{V}_l$. The dynamics of the two VSC are modeled by first order time delay elements (PT₁-Elements) with a time constant in the range between 15 and 30 ms [2].

In the model, the outputs of the operating point controllers are directly used by the converter control model for the calculation of $\bar{V}_l$ and $\bar{I}_q$. Furthermore a controller for improving the small signal stability of the system (damping controller) is implemented which will be dealt with in section 10.3. The outputs being fed back by the controller are the deviations from the setpoint values of active-power (ΔP_{ij}), reactive-power (ΔQ_{ij}), nodal voltage (ΔV_i) and the corresponding serial current (ΔI_i). The controller function is defined in equation 10.1. Its input and output vectors are defined in equations 10.2 and 10.3.

$$\Delta \mathbf{u} = -\mathbf{F} \Delta \mathbf{y} \quad (10.1)$$

$$\Delta \mathbf{y} = \left(\Delta V_i \quad \Delta Q_{ij} \quad \Delta P_{ij} \quad \Delta I_i \right)^T \quad (10.2)$$

$$\Delta \mathbf{u} = \left(\Delta u_{V,D} \quad \Delta u_{Q,D} \quad \Delta u_{P,D} \right)^T \quad (10.3)$$

10.2.2 Generic Rules for Coordination

Coordination for the steady-state operation can e.g. be performed using optimal power flow techniques [3]. Concerning the dynamical operation, an adaptation of the control operations by FACTS-devices to changing operating situations or critical events in the power system has to be performed.

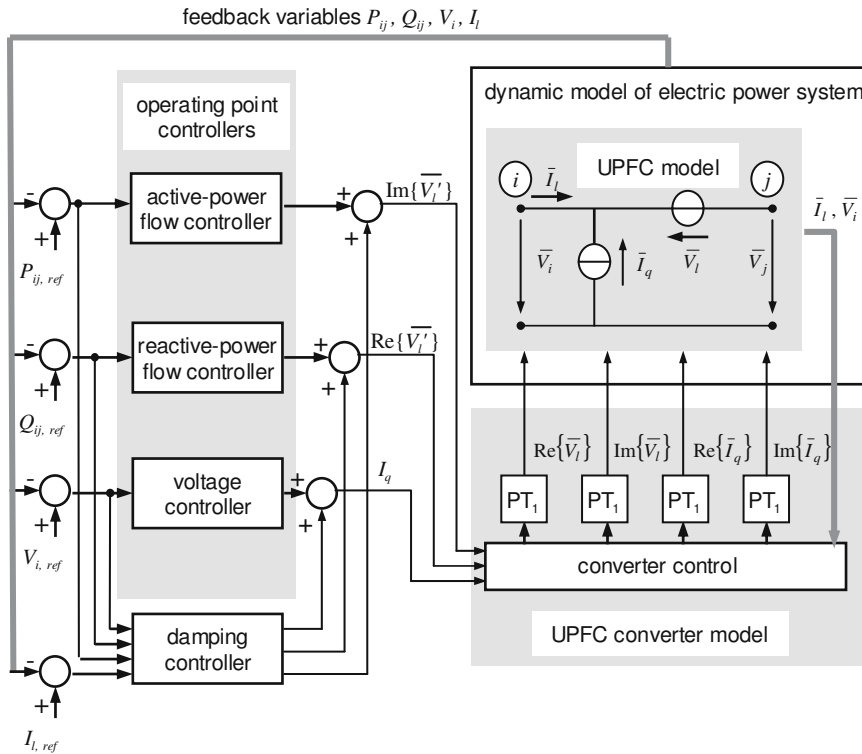


Fig. 10.1. UPFC modeling and control

Critical events, which require coordinating control measures to be applied to the embedded FACTS-devices, are:

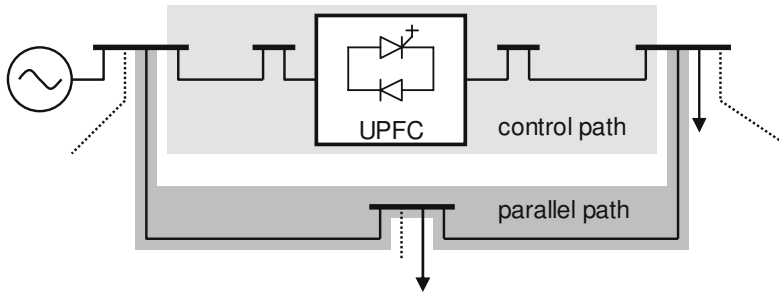
- overloading of electrical devices,
- failure of electrical devices,
- short circuits in transmission elements,
- changes of the system's state.

Necessary coordinating control measures have to be applied in short term range after the occurrence of one of the above-mentioned events. The first three events are emergency cases requiring fast actions. The fourth one concerns the damping control and will be analyzed in section 10.3.

The coordinating control measures can be formulated in a knowledge-based form as so-called generic rules [4]. Before they will be listed and explained, the definition of the terms 'control path' and 'parallel path', which concern the network topology, has to be given (see Table 10.1). For illustration, the topology of a simple example power system including one UPFC is shown in Figure 10.2.

Table 10.1. Definition of terms

Term	Definition
control path	transmission path in which a power flow controlling device (e.g. UPFC) is implemented and which only has junctions at its end-nodes
parallel path	transmission path which starts and ends at the same nodes as a control path and in which no power flow controlling device is implemented

**Fig. 10.2.** Simple example power system used for definition of control and parallel paths

The existence of a parallel path is an essential necessity for a power flow controlling FACTS-device. Controlling the power flow over its control path a FACTS-device shifts the power flow from its control path to parallel paths and vice versa.

A system theoretical analysis shows the following four coordinating control rules:

1. **IF** a device on a parallel path of a FACTS-device is overloaded,
THEN modify the P -setpoint-values of the FACTS-device

A power flow controlling FACTS-device can directly influence the active and reactive power flow over its control path. This leads to the above-mentioned shift of the power flow from the control path to parallel paths or vice versa. Consequently, power flows over parallel paths can be specifically influenced by changing the setpoint values for the active- and reactive-power flow of the control path. In this way overloadings of devices on parallel paths can be suppressed by changing the setpoint values of a power-flow controlling FACTS-device. The control path takes over the surplus of power flow which otherwise leads to the overloading of the device(s) on a parallel path.

This rule recommends modifying only the P -setpoint-values of FACTS-devices to suppress overloadings because these are mainly caused by active power flows. The reactive power-flow controlling functions of a FACTS-device can then be used for voltage control.

2. **IF** there is a failure of a device on a parallel path **AND** no further parallel path exists for a FACTS-device
THEN deactivate the power flow controllers of the FACTS-device

The existence of at least one parallel path to a control path is an important condition for the reasonable application of the power flow control function of a FACTS-device. As already described above, power flow control causes a shift of the power flow between control path and parallel path(s). Hence, if a failure of a device causes an opening of all parallel paths, the power flow control of a FACTS-device is hindered. The consequence would be that the outputs of the FACTS-device's power flow controllers would run into their limits, which may cause strong system oscillations. This is called 'false controlling effect', which means that the power flow controllers try to meet the given setpoint values, but they cannot reach them because power flow can not be shifted to parallel paths. According to the NISC requirements this needs to be avoided. By quickly deactivating the power flow controllers after such a failure the false controlling effect can effectively be prevented.

3. **IF** a short circuit happens on a control path or on a parallel path of a FACTS-device,
THEN slow down the operating point controllers of the FACTS-device

This coordinating measure prevents excessive power oscillations after a short circuit followed by automatic reclosing. The reason for this is that the power flow changes drastically during the short circuit. Mainly, a high reactive current flows over every line into the direction of the short circuit location. Because of the short response time of the FACTS-devices the power flow controllers respond immediately to the short circuit and try to meet the preset setpoint values. Also the voltage controller tries to fix the setpoint-voltage. Hence, the outputs of the operating point controllers will strongly increase within a short period of time and reach their limits even before the fault is clarified and the automatic reclosing is started. When the fault is removed after an automatic reclosing these large values of the manipulated variables of the operating controllers lead to strong oscillations. This is another kind of false controlling effect and has to be suppressed by suitable measures. Through slowing down the power flow controllers and the voltage controller during the short circuit and the automatic reclosing (decreasing of the PI controller parameters) this false controlling effect can be prevented.

The correct application of these three coordinating measures to FACTS-devices and their control enables the network operators to exploit the advantages being offered by FACTS for their steady-state and dynamical secure operation. The autonomous control system is designed to execute them automatically.

10.2.3 Synthesis of the Autonomous Control System

Due to the continuous changes of the operating states and the topology during the daily operation through varying loads, generations and switching operations, the

specific coordinating control measures must be followed up automatically to these changes. Only under this condition the controller is able to react adequately on critical events in the changed system. This guarantees a dynamical and stationary secure behavior of the whole system. To ensure a quick reaction of the autonomous system, the specific coordinating measures have to be derived, before a critical event occurs. Hence, topology-changes of the network have to be analyzed continuously. This continuous adaptation of the specific coordinating measures for changing topologies is called 'preventive coordination' being performed by the autonomous control system. The three coordinating generic rules, which have been explained in the previous section, are the elementary tasks, which have to be fulfilled by the autonomous control system.

These first three rules mainly concern setpoint values for the operating point controllers and the operating controller's parameters. The development of the autonomous system is performed successively starting at the bay control level. Some elementary autonomous components are chosen and designed to be acting on this control level. After that, additional autonomous components on the other control levels are added. They provide the components on the bay control level with necessary specific information, which is generated automatically in dependence on the actual network topology.

10.2.3.1 Bay Control Level

Figure 10.3 shows the operating point controllers of a UPFC, which are extended by the additional controllers as autonomous components on the bay control level. They perform the basic measures, which are required by the first three generic rules and are explained in the following.

The coordinating measure given by the first generic rule requires a modification of the P -setpoint value of the UPFC in order to prevent overloadings on lines on its parallel paths. A simple but effective autonomous component performing this can be an integral-action controller forming an outer control loop. The actual active-power flows over all lines on parallel paths have to be observed by the autonomous component. As the degree of freedom for influencing power flows over parallel paths of one FACTS-device is equal to one. A UPFC can at the same time specifically prevent only one overloaded line. If several overloadings are detected, the line with the biggest overloading is chosen.

The actual deviation from the maximum allowed active power flow ($P - P_{max}$), which has a positive value in case of an overloading, is taken as the input of the integral-action controller. This way it adjusts the setpoint of the active-power flow controller of the UPFC until the active-power flow of the overloaded line is reduced to its maximum allowed value P_{max} . This is the basic idea of how the first generic rule is implemented on the bay control level. It guarantees the steady-state security of the power system.

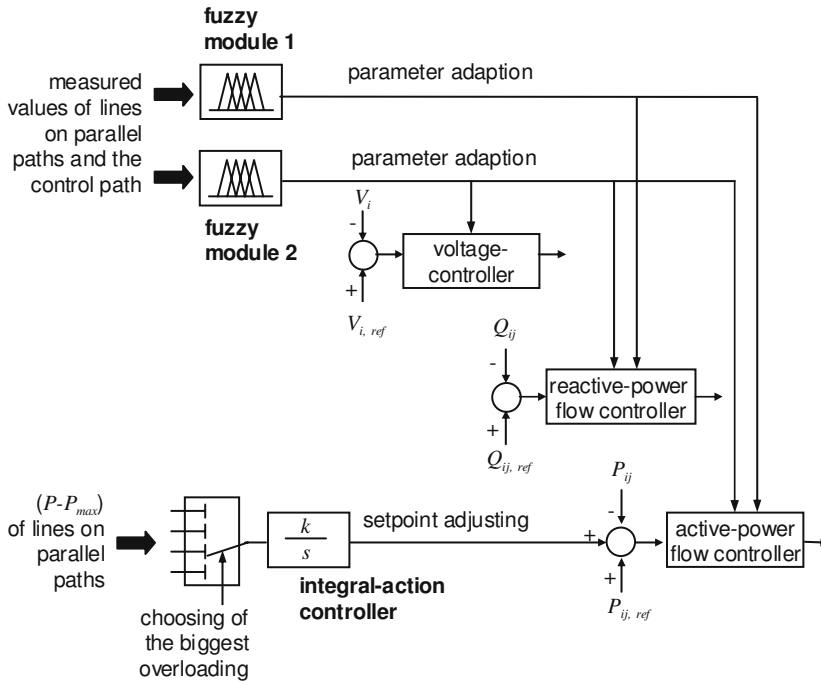


Fig. 10.3. Operating point controllers of a UPFC with autonomous components on the bay control level

When using this method in practice several additional measures have to be implemented. This comprises e.g. the detection if the reason of an overloading has disappeared after the overloading has been removed by the integral-action controller. In this case the setpoint adjusting by the integral-action controller has to be reset. Another important issue is the detection if an overloading is permanent or only temporary. Temporary overloadings can appear in case that the active power flow over a line oscillates around a value, which is directly below the maximum capacity. Those temporary overloadings are usually uncritical because they do not cause thermal problems. Hence they do not have to be treated by the autonomous control system. Additionally, it has to be respected that not all overloadings of lines on parallel paths can be removed by the P -setpoint adjusting. It strongly depends on the impact of a FACTS-device on the power flow of parallel paths, which can be high or very low. In case the impact is very low, usually a very big change of the P -setpoint is required for removing the overloading. As the UPFC has only limited control power, the setpoint adjusting will probably not be successful when trying to remove the overloading. These and further specific aspects are very important for the implementation of the method.

The second generic rule requires a deactivation of the power flow controllers in case of failures of distinct devices on parallel paths. The deactivation of the con-

trollers shall be performed by quickly setting the controller parameters of the active and reactive power flow controller to zero. Adaptive control is chosen to be suitable for this. Since fuzzy adaptation provides a transparent knowledge based implementation of adaptation rules, a fuzzy module is chosen to be the autonomous component on the bay control level performing this task (fuzzy module 1).

In addition, such a fuzzy adaptation produces soft transitions between the activation and deactivation of the controllers. The knowledge bases are derived from the generic rule 2. This is performed by autonomous components on higher control levels and will be described in a later section. The input quantities of the fuzzy controller must be measured values of lines on parallel paths. From these input quantities the fuzzy controller must be able to clearly recognize failures of relevant transmission elements. Measurements of the currents or complex power flows over the concerning transmission elements can be taken as input quantities. Membership functions for the input quantities have to be chosen once and remain valid for all operating cases.

The implementation of the third generic rule on the bay control level is also done by a fuzzy controller performing an adaptation of the parameters of the operating controller (fuzzy module 2). It decreases the operating point controller's parameters in cases of short circuits on lines of the control path or on parallel paths so that the controllers are slowed down strongly, as it is required according to generic rule 3.

Short circuits (faults) must be reliably recognized by the input quantities of the fuzzy controller. Hence, the currents over those lines can be taken as input quantities for the fuzzy controller. Also here the membership functions have to be chosen only once.

10.2.3.2 Substation and Network Control Level

Autonomous components on the substation and the network control level have to generate specific additional information for the autonomous components on the bay control level (fuzzy modules, integral-action controller and damping controller). This must also be based on the generic rules.

The generic rules strongly depend on the network topology. They use the terms 'control path' and 'parallel path' as they have been defined above. For this reason, autonomous components on the network control level have at first to analyze automatically the network's topology. This is done recursively with the known backtracking technique. The result is an assignment of all parallel paths to each control path. For large and complex networks these calculations can take long computation time because theoretically a large number of parallel paths may exist. However, since the impact on parallel paths that are far away from the control path may be very small, the user can define a reasonable area of impact for each FACTS-device, in which it has sufficient impact on its parallel paths. These areas should be chosen such that the influence of the power flow over lines within the areas can be performed with a realistic amount of control power. The analysis of the network's topology for finding control and parallel paths can then be limited to these areas of impact.

With the result of the topology analysis the three generic rules can be brought to a set of concrete coordinating rules, which are valid for the actual network topology. To illustrate this, one example of a concrete rule for each generic rule shall be given:

1. **IF** line 11-19 is overloaded **THEN** modify the P -setpoint-values of UPFC 2
2. **IF** there is a failure of line 17-18 **THEN** deactivate the power flow controllers of UPFC 1
3. **IF** a short circuit happens on line 11-19 **THEN** slow down the operating point controllers of UPFC 2

This is how the rules may look like for an example real power system containing UPFCs. The complete sets of concrete coordinating rules may contain a large number of rules.

For the generic rules 2 and 3 the concrete rules are then translated by autonomous components into fuzzy rule bases for the fuzzy modules 1 and 2 on the bay control level for each FACTS-device. The rule bases are downloaded into the fuzzy modules 1 and 2.

Concerning generic rule 1 the result of the topology analysis is used by a further autonomous component to compute the impact of the FACTS-devices on lines on parallel paths. It computes the GSDF (generation shift distribution factors, [5]) in order to quantify the impacts of FACTS-devices on all lines of the parallel paths. Only if the impact of a FACTS-device on a line is big enough, it is sensible to include this line into the autonomous control in terms of preventing overloadings. If more than one FACTS-device has a certain impact on a line, the FACTS-device with the biggest impact on that line is determined to remove a possibly occurring overloading. This way the GSDF determine the lines, which have to be monitored by which FACTS-device with regard to overloadings. They also determine the parameters k of the integral-action controllers. This mainly concerns the sign of the control action, which means if the P -setpoint has to be increased or decreased to remove a specific overloading of a transmission element.

In this way it can be guaranteed that the integral-action controllers perform their control actions to remove overloadings with the correct direction and the necessary intensity.

Figure 10.4 finally shows the autonomous components, which are necessary on the substation and the network control level in order to generate specific information for the fuzzy modules and the integral-action controllers as autonomous components on the bay control level.

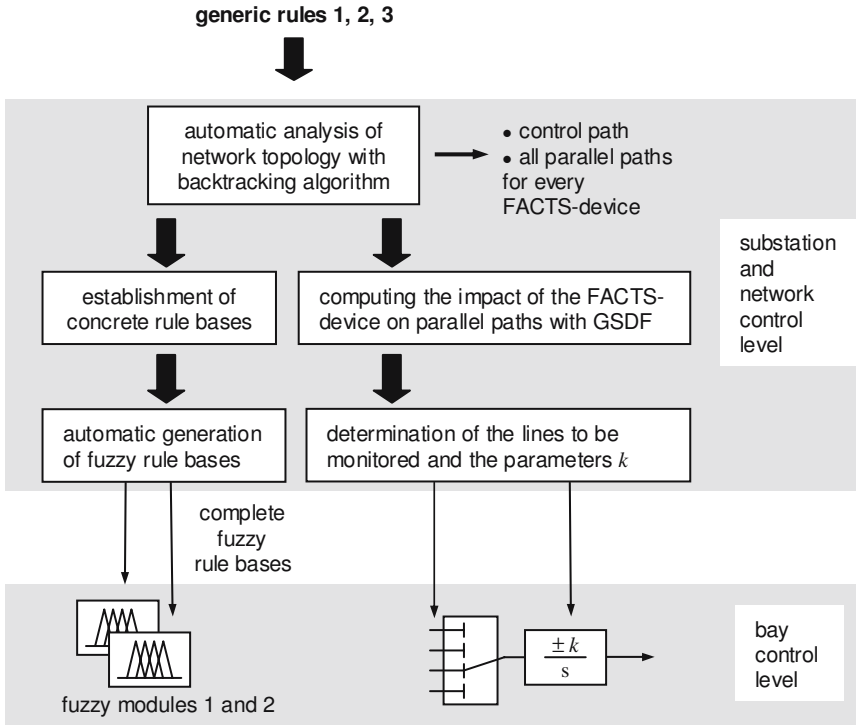


Fig. 10.4. Autonomous components on the substation and network control level for generic rules 1, 2 and 3

10.2.3.3 Preventive Coordination

As already mentioned before, the specific information for fuzzy and integral-action controllers (fuzzy rule bases etc.), which represent the coordinating measures in the case of overloadings, faults, and failures, is only valid for the network topology for which they have been generated. Since the topology of the system changes in the daily operation of the power system by switching operations, the fuzzy rule bases and additional information for the integral controllers must be followed up automatically to these modifications. Only under this condition it is guaranteed that the autonomous system can react correctly to critical events according to the above-mentioned generic rules. Such planned changes of the network topology are named in Fig. 10.5 with 'intended topological changes'. In addition, the occurrence of critical events, to which the autonomous system reacts by means of fuzzy parameter adaptation or setpoint adjusting, itself may lead to a changed topology, for instance through the unintentional failure of a transmission line.

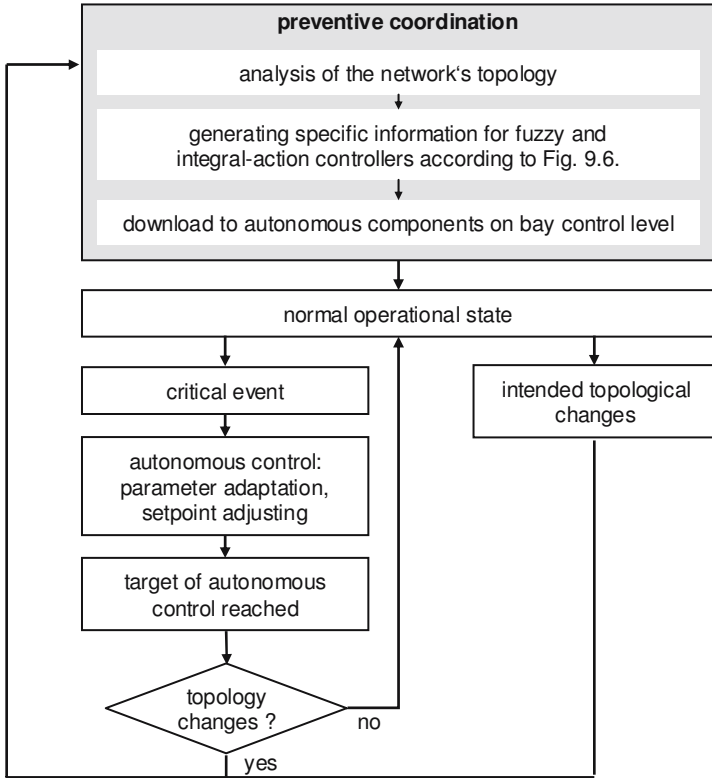


Fig. 10.5. Procedure for preventive coordination of FACTS-devices

For both cases of topology changes the previously described procedures for the generation of specific information for fuzzy and integral-action controllers being performed by autonomous components on the substation and the network control level have to be activated automatically.

Hence, new specific information is generated for the autonomous components on the bay control level. This is called 'preventive coordination'. The term 'normal operational state' means that at the moment no certain coordinating action of the autonomous system is required so that only the operating point controllers are in normal operation. 'Target of autonomous control reached' indicates that an overloading has been successfully removed or that operating point controllers have successfully been slowed down or deactivated in order to prevent false controlling effects respectively.

10.3 Adaptive Small Signal Stability Control

From a control systems theory point of view, an electric power system behaves like a non-linear, time-variant controlled system. Due to permanent changes of power generation, loads, and the networks topology, the dynamical state of the system varies strongly and continuously. FACTS-devices, which are equipped with simple damping controllers like a linear output feedback controller, shall improve the small signal stability of a power system during all its operating conditions. Therefore the controller has to be continuously adapted according to the changes of the dynamical states, which happen to the entire system.

The damping controller in Figure 10.1 is usually implemented to work in parallel to the operating point controllers, which means that the outputs of the damping-controller are added to the outputs of the operating point controllers. For example an output feedback controller with adaptable parameters can be used to improve the system's small signal stability. This controller is linear and it is usually parameterized for a power system model being linearized around an operating point. Constant parameter settings can usually only guarantee good control performance for the system operating around this point and not within the whole range of states in which it can operate. Hence, the damping controller parameters are to be adapted to changes of the system's state.

A fourth generic rule can be formulated to take this requirement into account.

4. **IF** a change of the dynamical state of the entire system happens,
THEN adapt the parameters of the FACTS-device's damping controller.

10.3.1 Autonomous Components for Damping Control

The damping controller is designed as an output feedback controller whose feedback matrix F has to be adaptable to changing conditions of the power system according to generic rule 4.

The bay control level does not contain any specific autonomous components for the adaptation of the damping controller since information about the whole system's state can only be provided from the entire power system point of view, i.e. from the network control level.

Autonomous components on the network and substation control level have to determine the damping controller parameters, i.e. the elements of the output feedback matrices F of each FACTS-device being fitted with such a damping controller. As already done in the previous sections of this chapter, the ideas and concepts of how this is performed shall be revealed instead of presenting all details about their implementation.

As mentioned above, loads, generations and the network's topology determine the dynamical state of the power system as a controlled system, its input variables and its equivalent transmission function. The non-linear system equations for a current operating point can be linearized around this operating point, such that a set of linear coupled differential equations is received. Hence, the power system

can be described as a first-order state space model, which is valid in a certain environment around the chosen operating point.

The computation of the eigenvalues of the system matrix A gives information about its oscillatory characteristics, e.g. critical modes. Critical oscillation modes are modes with a small or even negative damping ratio. Furthermore, the eigenvalues have to be computed by an autonomous component in order to determine the modal transformation of the system. This is also done on the network control level. Regarding the input matrix B_m of the modal transformed system it can easily be analyzed, which FACTS damping controller has got a strong influence on which of the critical oscillation modes of the system.

The autonomous components assign to the critical mode with the lowest damping ratio one FACTS-device, whose damping controller has the biggest influence on that mode. The remaining FACTS-devices are then one by one assigned to other critical modes with higher damping ratios.

Using this selection and some further information, like the damping sensitivity factors (DSF) [6], a cost function is formulated which expresses the effectiveness of a chosen parameter set for the FACTS damping controllers, concerning the resulting damping ratios of the critical modes in the closed-loop operation. This cost function is then minimized using the well known Simulated Annealing algorithm as a numerical optimization technique [7] in order to determine the optimal output feedback control matrices F_i for each existing FACTS damping controller and the present system's state. Fig. 10.6 illustrates the whole described procedure being performed by autonomous components on the network control level in order to compute optimal FACTS damping controller parameters after a change of the dynamical state of the entire system.

10.4 Verification

In the following, two simulation examples are shown in order to illustrate the performance of the autonomous control system. For the investigations the example network according to Fig. 10.7 has been analyzed. The fuzzy rule bases and global information for integral controllers were generated with the described autonomous system, which has also been implemented into a simulation environment.

A failure of a transmission line and the scenario of a line overloading caused by a rapid increase of a load is simulated. In this way the effectiveness of the coordinating measures through generic rules 1 and 2 is shown. The per-unit quantities of the used example power system are: $S_b = 1250$ MVA and $U_b = 400$ kV.

The example system is derived from the extra-high voltage level of large power system, which has been reduced to the essential transmission elements, generators and loads.

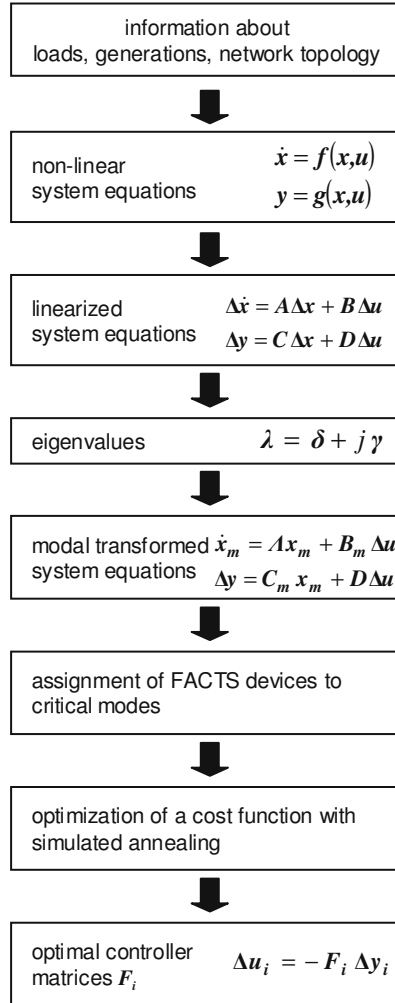


Fig. 10.6. Procedures being performed by autonomous components on the network control level for the automatic adaptation of FACTS damping controller parameters after changes of the dynamical system state (index i denotes the i -th FACTS-device, if several FACTS-devices are installed in the power system)

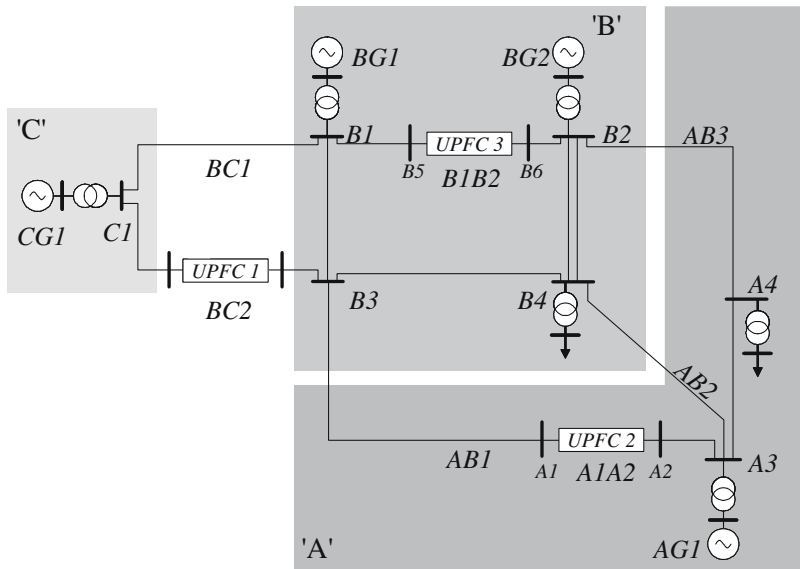


Fig. 10.7. Topology of the test system

10.4.1 Failure of a Transmission Line

A failure of line *BC1* is assumed. It occurs at $t = 0.1$ s with a duration of 4.9 s. Line *BC1* has before been correctly identified as a part of a parallel path of UPFC 1 by the topology analysis. The results of the automatic topology analysis are listed in Table 10.2.

The control path of UPFC 1 has only one parallel path. This means that there is no parallel path existing after the failure of this transmission line. Without autonomous control the controllers try to keep the setpoint value for active and reactive power flow over UPFC 1 and produce a large value for V_l up to its limit of 0.15 pu (see Fig. 10.8). This is due to the false controlling effect. However, the setpoint values cannot be kept because of the missing parallel path. This large value of V_l produces strong power oscillations during the failure of the line. They can be seen in Fig. 10.9.

Table 10.2. Result of the automatic topology analysis

FACTS-device	UPFC 1	UPFC 2	UPFC 3
control path (node numbers)	<i>C1-B3</i>	<i>B3-A3</i>	<i>B1-B2</i>
parallel paths (node numbers)	<i>C1-B1-B3</i>	<i>B3-B4-B2-A4-A3</i> <i>B3-B4-A3</i>	<i>B1-B3-B4-B2</i> <i>B1-B3-B4-A3-A4-B2</i>

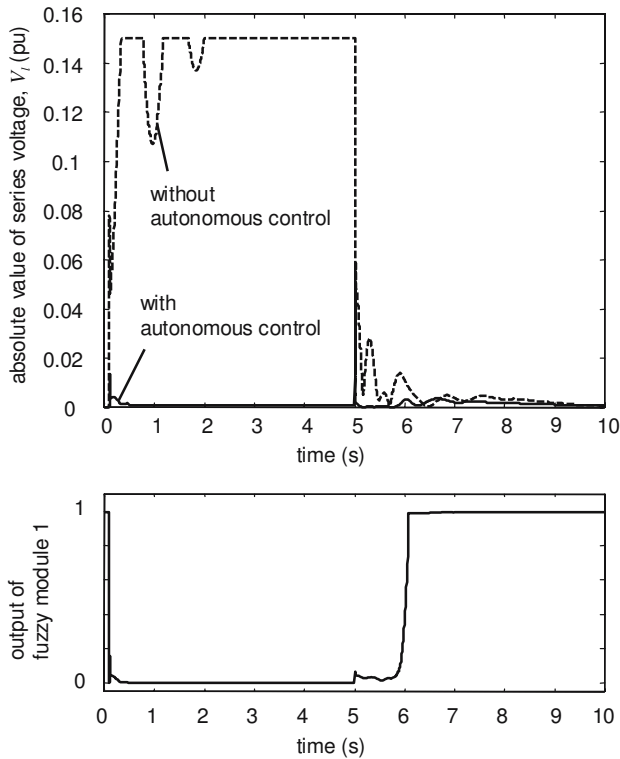


Fig. 10.8. Series voltage of UPFC 1 (above) and output of fuzzy module 1 of UPFC 1

When the autonomous control system is in use, fuzzy module 1 for the generic rule 2 in UPFC 1 reacts immediately by deactivating the power flow controllers. The effect is visible in Fig. 10.8 with the output of the fuzzy module and the resulting outputs of the power flow controllers. The two power flow PI-controllers of UPFC 1 only cause a small increase of the manipulated variables during the failure. Consequently, the oscillations in the system are calmer during the failure than without the application of the autonomous control system.

It has to be mentioned that the shown effect only results from the slowing down of the controllers in order to prevent the false controlling effect. No FACTS damping controllers are present within that system. The damping could even be further improved if FACTS damping controllers were used.

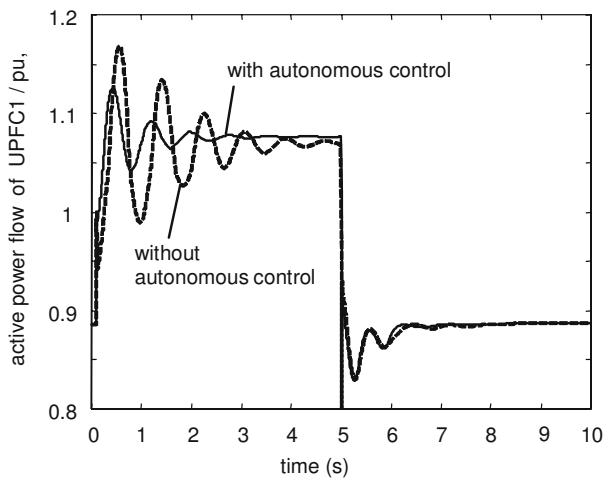


Fig. 10.9. Active power flow over UPFC 1

10.4.2 Increase of Load

After an increase of the system loads the primary controllers of the power plants operate in order to cover the supplementary power requirement. Independent of this the three UPFC fix the power flows over the control paths constant with their fast power flow controllers. Consequently, they can for this moment not be used for the transmission of primary control power.

The capacity of line *AB2* is used to approximately 94 % before the load increase. A sloping increase of the system loads of 14 % happens at $t = 1$ s. The primary control power generated by *AG1* has to be transmitted to the load at node *B4* e.g. over line *AB2*, since the control of UPFC 2 first keeps the unchanged setpoint values. Without the autonomous control system a non-permissible overloading of *AB2* occurs (see Fig. 10.10). If this condition continued, a tripping of the transmission line would be inevitable.

In the topology analysis, which has been executed before by the activated autonomous control system, this line is recognized as an element of a parallel path to UPFC 2, so that its integral-action controller counteracts directly on the line overloading and increases the setpoint value for the active power flow (see Fig. 10.10, below). This causes a shift of the power flow and a relief of *AB2*, so that its maximum loading limit of 0.62 pu (active power) can be kept (see Fig. 10.10, above). At $t = 1000$ s the loads are decreased to their original values, which means that the reason for the overloading has now disappeared. This has been simulated to show that the autonomous control system is able to reset itself when its coordinating control actions are not needed any more. The integral-action controller reduces its output back to zero.

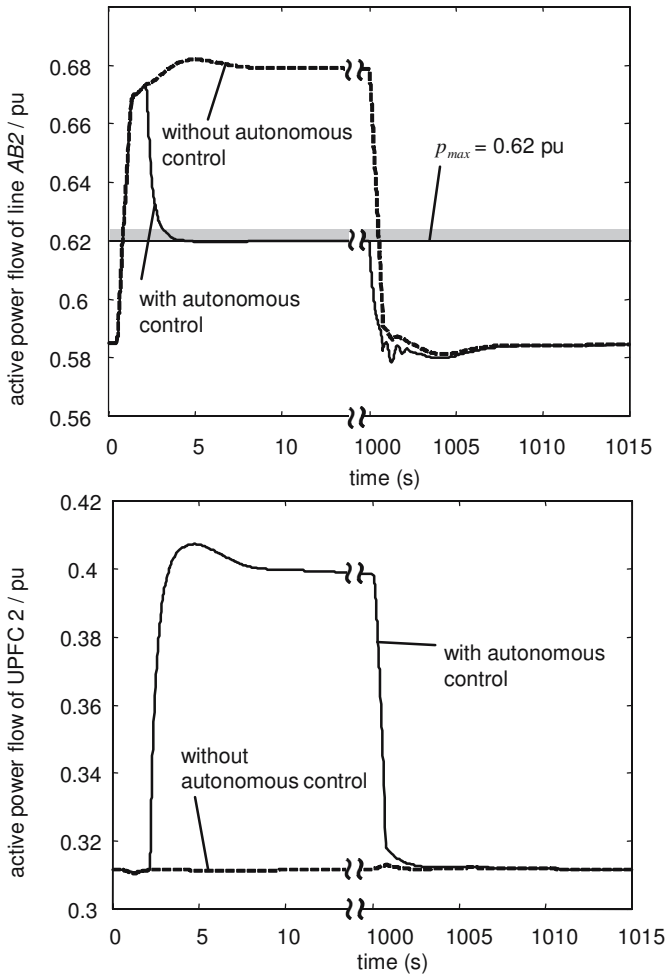


Fig. 10.10. Active power flow over line AB2 (above) and active power flow over UPFC 2 (below)

In conclusion, the use of FACTS-devices offers a flexible management of network-operation from a technical and economical point of view. Beyond this they may cause many negative effects, which occur due to their short response time after critical events. Hence their advantages can only be used if automatic, quick, intelligent, and preventive coordinating measures are performed to eliminate those negative effects. The theory of autonomous systems offers a structural approach for a coordinating control system for FACTS-devices. The necessary coordinating measures, which have to be executed by an autonomous control system, can be formulated as four generic rules. An autonomous control system has been devel-

oped and implemented for such a coordination so that the steady-state and dynamical system security is guaranteed after critical events. It automatically applies the four generic rules for every operation condition of a power system. The control system specifies the generic rules within several steps and on different control levels so that concrete information is made available for decentralized autonomous components. For this, several techniques of Computational Intelligence, such as Fuzzy Control and Simulated Annealing, as well as conventional control techniques are applied. The concrete information consists e.g. of fuzzy rule bases and damping controller parameters and is generated preventively. Hence, the reaction of the system is as fast as possible and correct for the present operating condition of the power system.

An open question in this section is how exchange online information between the parallel path, which means remote lines, and the FACTS controller. The following section will answer this question with wide area control systems. Another open issue is the basic design of the damping controller, because this chapter has only introduced a solution for the automatic adaptation, but not for the design itself.

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